

Energy Harvesting from Exercise Machines

Buck-Boost DC-DC Converter with the LT8705 Controller

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Abstract

In order to increase sustainability and save money, the Energy Harvesting from Exercise Machines (EHFEM) system uses human supplied energy to self-power exercise equipment such as spin bikes, elliptical trainers, ergometers, etc. This document covers the design and implementation of a Buck-Boost DC-DC converter using the LT8705 controller into the EHFEM system. This project improves upon the overall efficiency of the Buck-Boost Converter designed by past groups working on the EHFEM system.

Chapter 1: Introduction

The Energy Harvesting from Exercise Machine (EHFEM) system converts kinetic energy, provided by the user of an exercise machine, into electrical energy and sends it back to the grid. Doing this allows the Cal Poly Recreation Center, or any other recreation center that contains one of these machines, to reduce their utility costs. This report covers one design of the DC-DC conversion portion of the system. This design uses the LT8705 controller, a high performance buck-boost switching regulator controller, with a wide input and output range [3].

A DC-DC converter circuit converts one DC voltage to another. It contains an inductor, one or more switches and one or more diodes. The component layout determines the topology of the converter, each topology has different characteristics. Adding controllers, voltage sensing circuits and capacitors improves the performance of the converter [5].

The EHFEM system started in 2007, with Dr. David Braun and a group of ME and EE students modified an exercise bike to produce AC and DC power as a standalone system [9]. Since then, the project has grown to include multiple exercise machines and a system to send energy back to the utility grid. This system includes input protection circuitry, a dc-dc converter and an inverter. The input protection circuitry, added by Funsten and Kiddoo [8] and R. Turner and Z. Weiler [10], eliminates any voltage and current spikes entering the converter. Hilario determined that a four switch DC-DC converter applies best to the EHFEM system [11]. This led to the design of DC-DC converters for the system using a variety of different four switch DC-DC converters, such as, Burk, Bhula and McKay [4], Wong [7] and Chu and Yoo [12]. Concurrent senior projects selected the appropriate inverter and interfaced it with both the utility grid and the DC-DC converter.

This project intends to improve upon the design of Burk, Bhula and McKay, who also used the LT8705 controller in their DC-DC converter. In order to make the EHFEM system feasible for recreation centers to use, it must pay for itself over a reasonable amount of time so that the recreation center can use the machine to save them money. For this to happen, the EHFEM team continually improves upon the system with more streamlined designs and any new technology available. By doing so, the EHFEM system may soon become smaller and more efficient creating a bigger impact on the utility bill of recreation centers as well as on the sustainability of our environment.

The following chapters explain the purpose behind pursuing the project, go over the EHFEM system structure and requirements, and documents the planning, designing, testing and building phases of the project. This begins in chapter 2, with an assessment of the customer's needs and the systems specifications and requirements.

Chapter 2: Customer Needs, Requirements and Specifications

Customer Needs Assessment

This section addresses the customers involved in the EHFEM project and their specific needs from the system.

This product has both direct and indirect customers. The direct customer, Dr. Braun, may use this converter in the overall EHFEM system. His needs stem from the necessity of the converter to do the following:

1. Integration with the system.
2. Increase the overall output/input power efficiency produced by the system.
3. Physically fit in the system.

The indirect customer is the Cal Poly Recreation Center. By buying the EHFEM system, they also buy the converter. Their needs come from the financial benefits the system presents and the popularity the system has with their participants. Their major concerns align with the main limiting factors of the project. The main limiting factors of this project include the cost, efficiency and size. The cost part plays a major role not only in the material cost but also in the overall cost to the recreation center. In order for them to buy the product it must pay for itself over a reasonable amount of time. The efficiency with which the system converts the user energy to output power must remain high in order to speed up the process of repaying the cost of the system. Concerns arise with how their participants view the product. For this reason the size plays a big role, the system must stay at a size that does not change the functionality of the machine and risk discouraging the participants from using it. This has been determined through research of their motivation for buying the EHFEM system.

In the following requirements and specification section gives more information on how the system must operate in order to meet these needs.

Requirements and Specifications

The main project requirements include meeting required safety codes, keeping overall cost low and not altering the exercise machine's functionality. Without these requirements, the Cal Poly Recreation Center would not consider buying the finished product, rendering the project unsuccessful. The other requirements and specifications pertain to the factors required for the converter to function in a way that allows the exercise machine to operate under self-power.

Table 1: Buck-Boost DC-DC Converter Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
4	The efficiency of the average power output vs. the average power input exceeds 90%	In order to power the exercise machine the converter must have this efficiency.
3	Converts a 0 V-51 V input voltage to a 36 V output voltage	Creates an output voltage used to power the exercise machine.
3	Average input power must not exceed 260 W	Meets input ratings of the converter.
3	Average output power must not exceed 180 W	Meets input ratings of the inverter.
2-5	Total cost below \$200	This represents the maximum senior project reimbursement costs, and keeps the overall cost low, making the final product economically feasible for the customer.
2,5	Fits in a 4" x 4" x 1" package	Size must not alter the exercise machine's functionality.
3,5	Handles an input current up to 5.1 A spike	Input current must not alter the exercise machine's functionality.
3	Output voltage must not exceed ± 0.5 V tolerance range	Regulates the voltage sent into the exercise machine.
1,6	Heat output must not exceed 90 degrees Fahrenheit	Heat output could potentially change user functionality and increases customer cost.
1	Must meet IEEE 1547 safety standards [2]	In order to keep the exercise machine in legal standards.
1	Must meet National Electric Code (NEC) safety requirements	All wiring must up to legal standards.
1	Meets Restriction of Hazardous Substances (RoHS) compliance	Considers the sustainability and environmental impacts of the system.
1	Must meet National Electric Manufacturers Association (NEMA) 6 enclosure standard [20]	System must operate up to all applicable standards.
3	Has a connection port to connect to the rest of the EHFEM system	Converter must receive and send power from and to the EHFEM system.
Marketing Requirements <ol style="list-style-type: none"> 1. Maintain safety of machine 2. Low cost 3. Integrates with other system components 4. Improves efficiency 5. Reasonable size 6. Doesn't alter participant use of exercise machine 		

The requirements and specifications table format derives from [1], Chapter 3. Its contents give the values needed for the component selection and design of the converter and the compliances the converter needs to meet. The design phase also consist of the printed circuit board (PCB) layout. In order for the circuit to operate correctly when laid out on a printed circuit board, follow the guidelines below [3].

- The ground plane layer should not have any traces and should sit as close as possible to the power MOSFETs.
- Keep high current switching paths as compact as possible and do not run them parallel to signal traces.
- Use immediate vias to connect components to the ground plane. Use several vias for power components.
- No ground under the SW1 and SW2 pins.
- Flood all unused area on all layers with copper.
- Separate power and ground planes.
- Place switch M2 and M3 as close to the LT8705 controller as possible.
- Connect the sense resistor to switch M2 and M3 with a short and wide trace.
- Keep high voltage switching nodes away from small-signal nodes.
- Input and output capacitor's (-) nodes should connect as close as possible.
- The top driver boost capacitors should sit as close as possible to their respective BOOST and SW pins.
- Connect input and output capacitors as close as possible to the MOSFETs.
- Connect compensation and sensing networks as close as possible to the LT8705 controller.

Before getting to the design choices that go along with the above guidelines, the following chapter describes the EHFEM system using block diagrams and functional decomposition tables.

Chapter 3: Functional Decomposition

This chapter breaks down the functionality of the EHFEM system through the use of block diagrams and tables. It covers the main functionality of different systems, as well as their inputs and outputs.

The EHFEM systems takes in energy generated from the user physically moving the exercise machine and repurposes the energy to send back to the grid. The converter takes in voltage and current from the input protection circuitry and converts it to a usable voltage and current for the inverter. The entire EHFEM system diagram, shown in Figure 1, specifies the functional requirements shown in Table 3. Figure 2 shows the subsystem of the converter with its inputs and outputs described in Table 4.

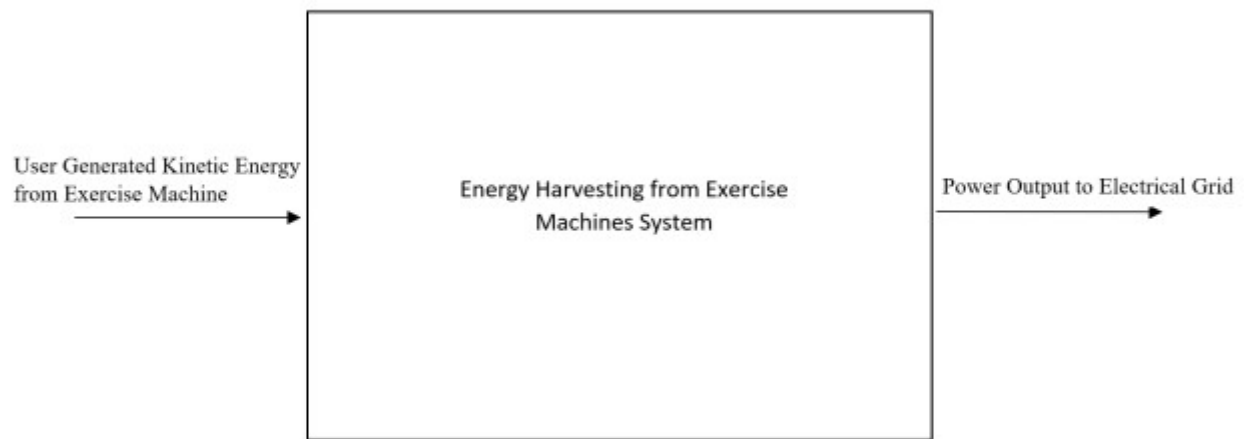


Figure 1: Block Diagram for EHFEM System

Table 2: EHFEM Functional Requirements

<i>Module</i>	Energy Harvesting from Exercise Machine System
<i>Inputs</i>	Input voltage ranging between 5V and 65V Max input current of 15A
<i>Outputs</i>	120V or 240V 60 Hz AC Voltage
<i>Functionality</i>	Convert the input voltage to a usable voltage for the rest of the EHFEM system.

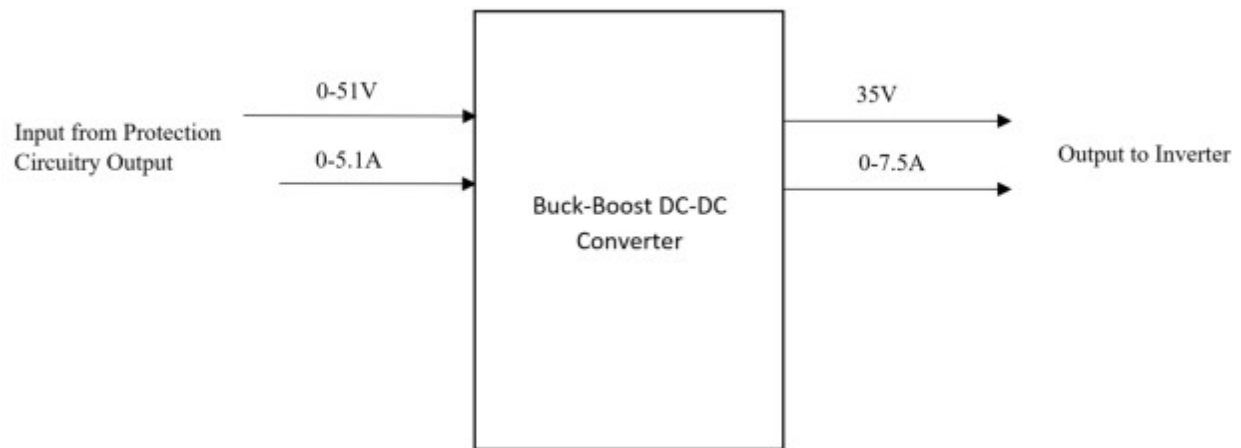


Figure 2: Level 0 Block Diagram for Conversion Sub System

Table 3: DC-DC Conversion Functional Requirements

<i>Module</i>	DC-DC Converter using LT8705 Controller
<i>Inputs</i>	Input voltage ranging between 0V and 51V Input current ranging between 0A and 5.1A
<i>Outputs</i>	Output voltage of 35V \pm 5% Output current ranging between 0A and 7.5A
<i>Functionality</i>	Convert the input voltage from the protection circuitry to a usable voltage for the inverter system.

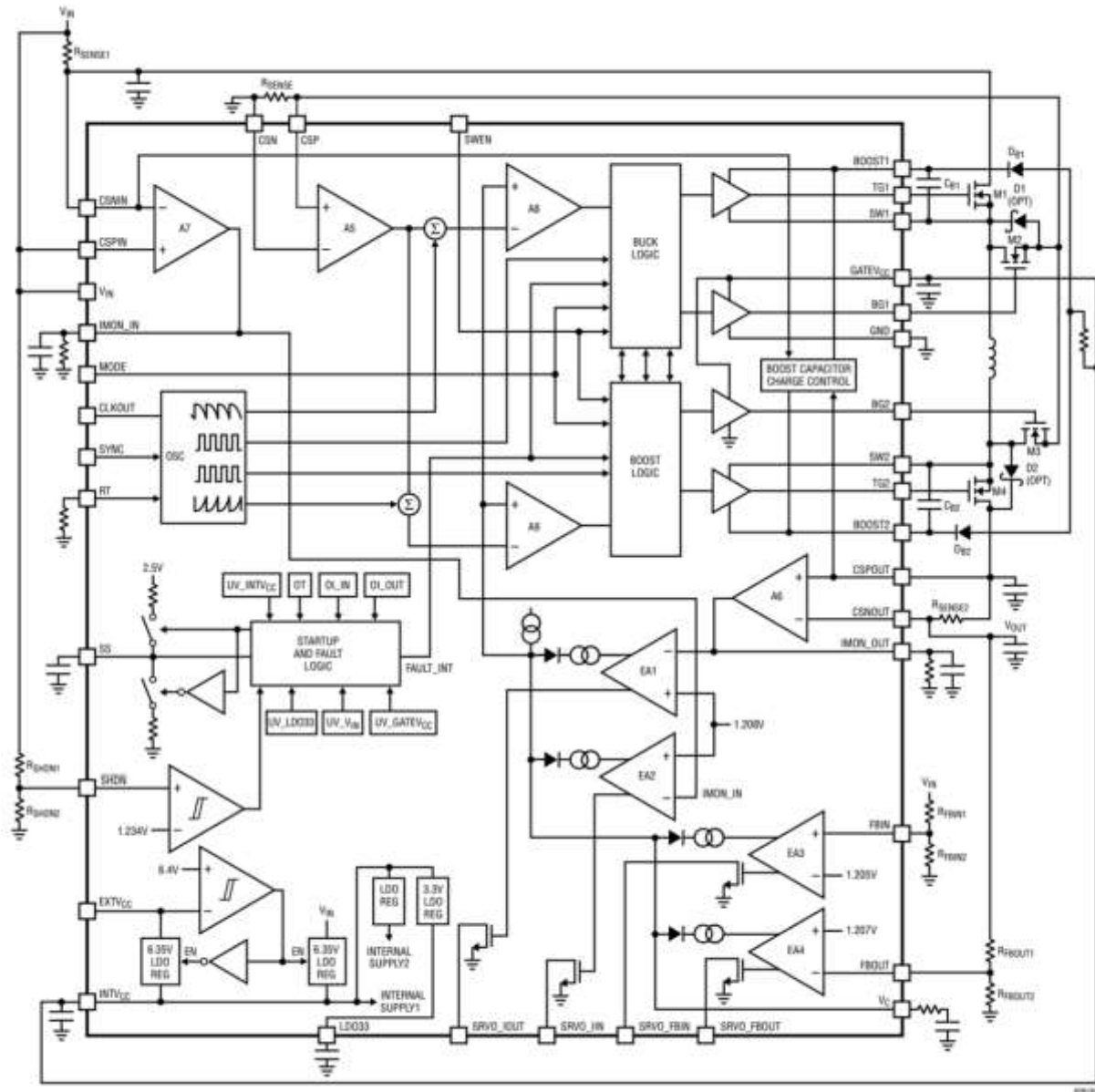


Figure 3: Level 1 LT8705 DC-DC Converter Block Diagram [3]

Table 4: Buck Converter Functional Requirements

Module	Buck Portion of Converter
Inputs	Input voltage ranging between 35V and 51V Input current ranging between 0A and 5.1A
Outputs	Output voltage of 35V \pm 5% Output current ranging between 0A and 7.5A
Functionality	The step down portion of the DC-DC converter. Converts voltages larger than the target output voltage to the target output voltage.

Table 5: Boost Converter Functional Requirements

<i>Module</i>	Boost Portion of Converter
<i>Inputs</i>	Input voltage ranging between 0V and 35V Input current ranging between 0A and 5.1A
<i>Outputs</i>	Output voltage of 35V \pm 5% Output current ranging between 0A and 7.5A
<i>Functionality</i>	The step up portion of the DC-DC converter. Converts voltages lower than the target output voltage to the target output voltage.

The following chapter outlines the proposed timeline to design, build and test the system described in this chapter. It also analyzes the difference between the proposed timeline and system costs and the actual timeline and system costs.

Chapter 4: Project Planning and Financial Analysis

This chapter covers the planned outline for project completion, the projected cost of the entire project and analyzes the actual costs.

Proposed Gantt Chart

The Gantt charts in Figures 4, 5 and 6 show the expected outline for EE 460, 461 and 462. Between EE 461 and 462, multiple design-test-build cycles are spaced out over 20 weeks while continuously compiling and analyzing design and test results.

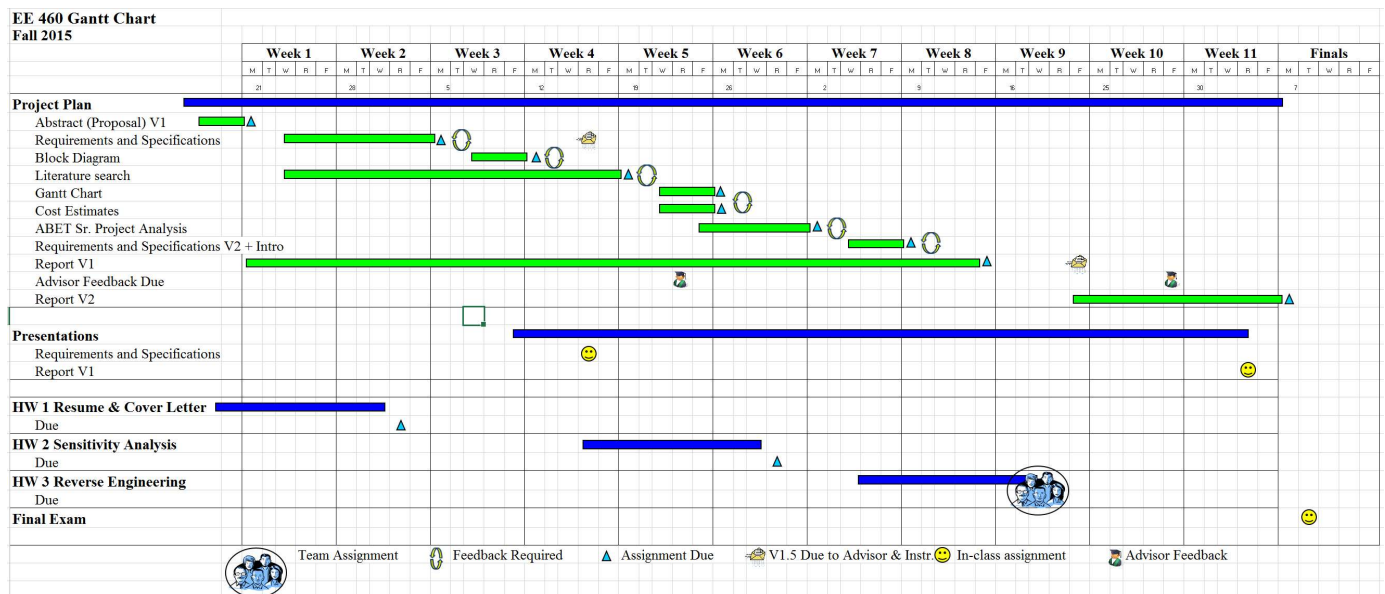


Figure 4: 460 Proposed Gantt Chart [21]



Figure 5: 461 Proposed Gantt Chart

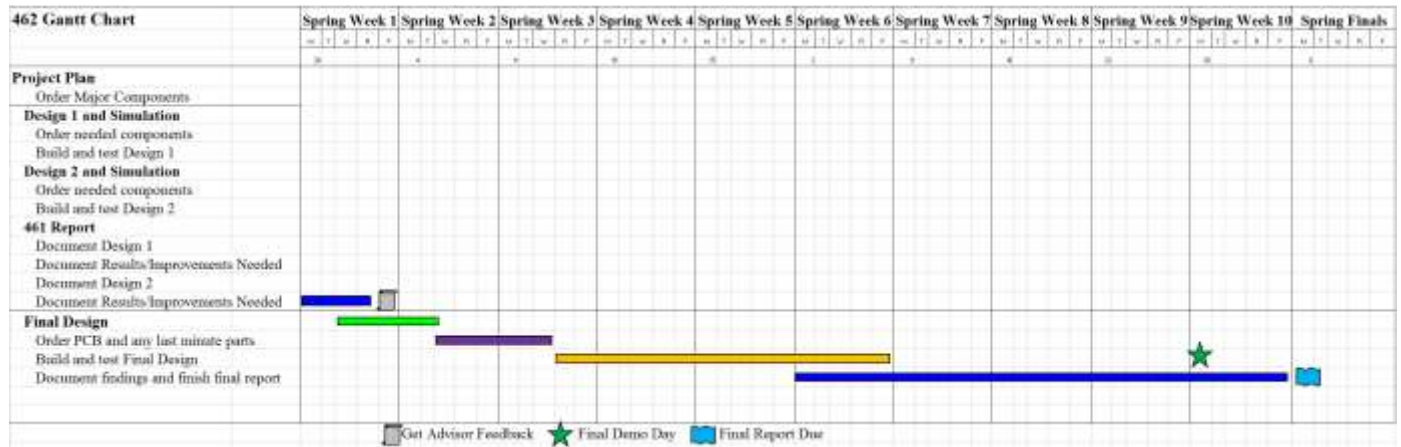


Figure 6: 462 Proposed Gantt Chart

Actual Time Breakdown

Project planning, in EE 460, followed the proposed Gantt chart shown in Figure 4. The design stage took much longer than originally estimated for. The PCB layout took five revisions and a quarter and a half before ordering a board. This left extremely little time for building and testing before the senior project exposition. Figure 7 shows the first three layout revisions in winter quarter. Figure 8 shows the final two layout revisions and the small building and testing time.

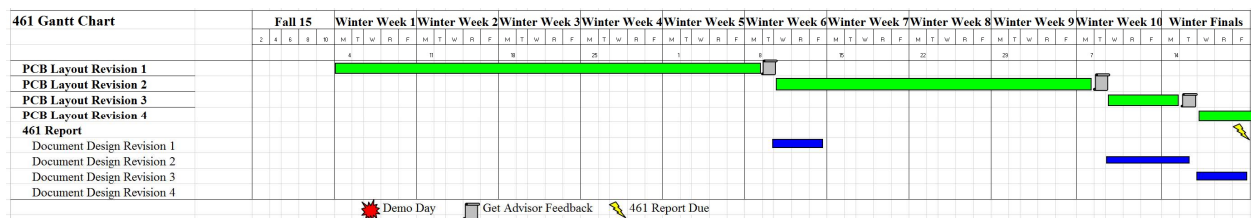


Figure 7: 461 Time Breakdown

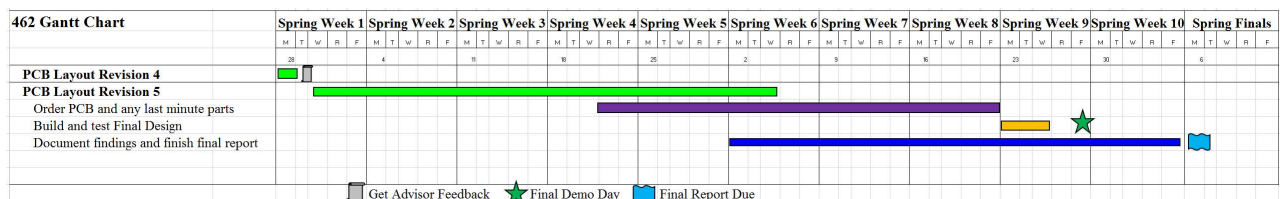


Figure 8: 462 Time Breakdown

Part Cost Estimate

Table 6 shows the expected cost of the final converter. The LT8705 controller, 4 layer board and resistors represent fixed costs. The other cost estimates depend on the specific components selected for the final design.

Table 6: Part Cost Estimate

Part	Quantity	Cost
LT8705 Controller	1	\$8.50
4 Layer Board	1	\$98.00
Resistors	18	\$0.90
Capacitors	14	\$28.00
Power MOSFETS	4	\$12.00
Inductor	1	\$1.00
Diodes	2	\$0.30
Heat Sinks	4	\$8.00
Total		\$156.70

Final Cost Breakdown

Table 7 shows the actual cost of the final converter. The board represents a bigger cost than originally estimated due to its final size. The capacitors did not cost as much as anticipated. Banana connectors did not appear in the original estimate. Most other components matched their estimated cost.

Table 7: Final Cost Breakdown

Part	Quantity	Cost
LT8705 Controller	1	\$8.50
4 Layer Board	1	\$149.10
Resistors	7	\$0.90
Capacitors	14	\$4.95
Power MOSFETS	4	\$14.71
Inductor	1	\$4.05
Diodes	2	\$0.47
Heat Sinks	4	\$6.60
Banana Connectors	4	\$6.46
Total		\$195.74

Labor Cost Estimate

The starting pay for an electrical engineer, according to [14], is \$64,000 per year. That equates to \$32/hr. After working on the project for the minimum number of hours required by the senior project requirements, 150, the total labor cost equates to:

$$\frac{\$32.00}{hr} \times 150 \text{ hrs} = \$4,800$$

Using the same equation for the maximum number of hours, 200, the total labor cost equates to \$6,400. The average of these two values gives the typical labor cost for the project, \$5,600.

The following chapter documents the layout considerations for the DC-DC converter. It covers five layout revisions, explaining the reasons for each change between revisions.

Chapter 5: PCB Layout

The PCB layout requires careful consideration in order to minimize noise, parasitic capacitance and inductance, temperature rise and board size. Without attention to detail in the layout process, the converter may not work as designed. For a list of design guidelines see Chapter 2's Requirements and Specifications section. Design of the layout uses ExpressPCB's layout and schematic software due to its simplicity and in house fabrication features [17].

Revision 1

The first PCB revision consist of a two layer board based on the converter design by Andrew Forster, shown in Figure 9. The major focuses of the first layout revision include, separating the power and signal components, attempting to route all traces on the top layer and orienting the four switches to reduce gate trace length and allow room for heat sinks.

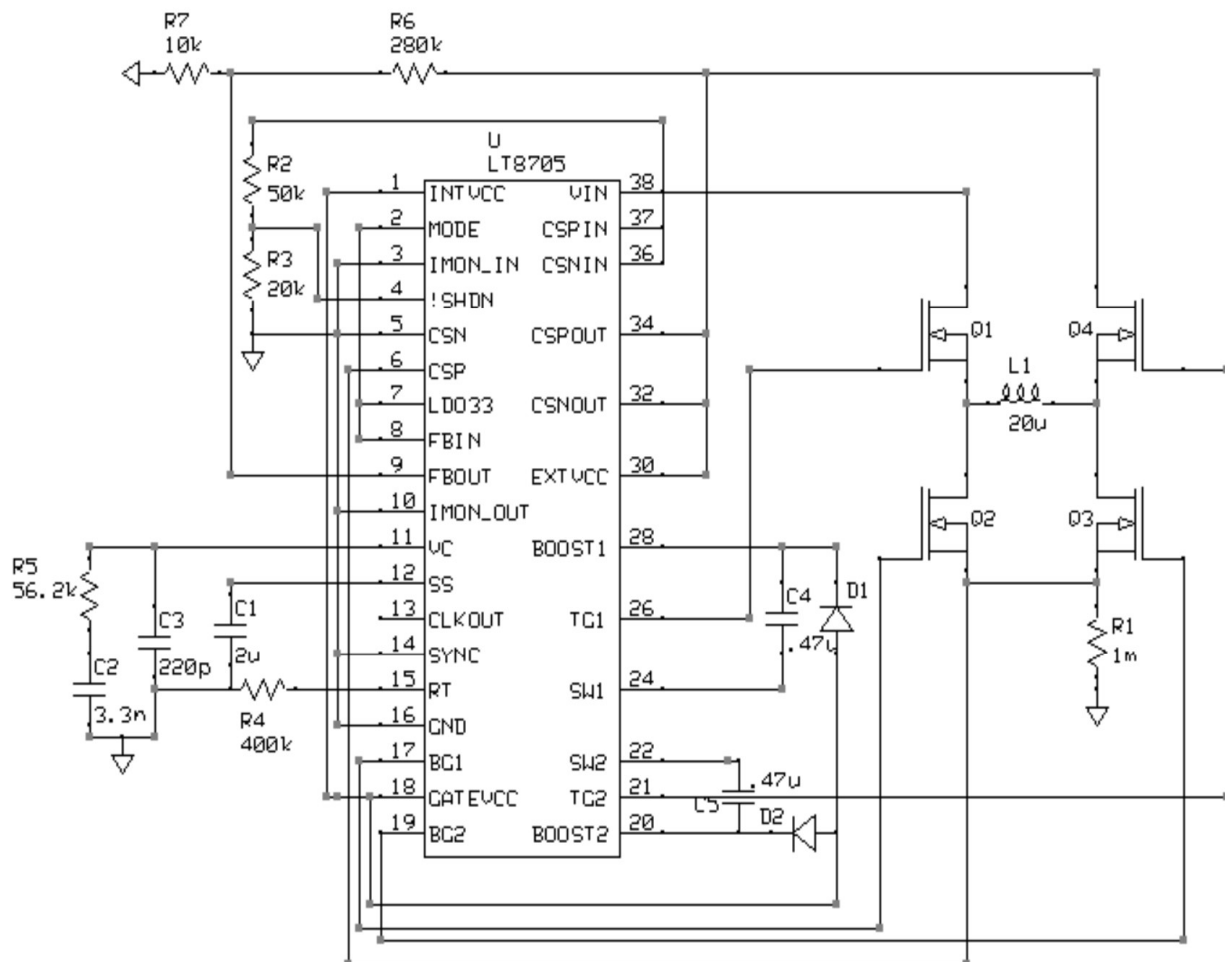


Figure 9: DC-DC Converter ExpressPCB Schematic

The first layout revision, seen in Figure 10, has red for the top copper layer and green for the bottom copper layer. The design contains many drawbacks, the two most critical being the length of the gate traces between the IC and the MOSFETs and the inability to route all traces on the top layer. The long gate traces add inductance to the circuit and limit the switching speed of the MOSFET. Having traces in the bottom ground layer violates the LT8705 datasheet's layout guidelines and causes complications with ground return paths. As shown by the red circle in Figure 11, the traces on the bottom layer of the PCB bottleneck the ground return path for the sense resistor. Other drawbacks include the lack of input and output capacitors and the lack of separation between power and signal ground planes.

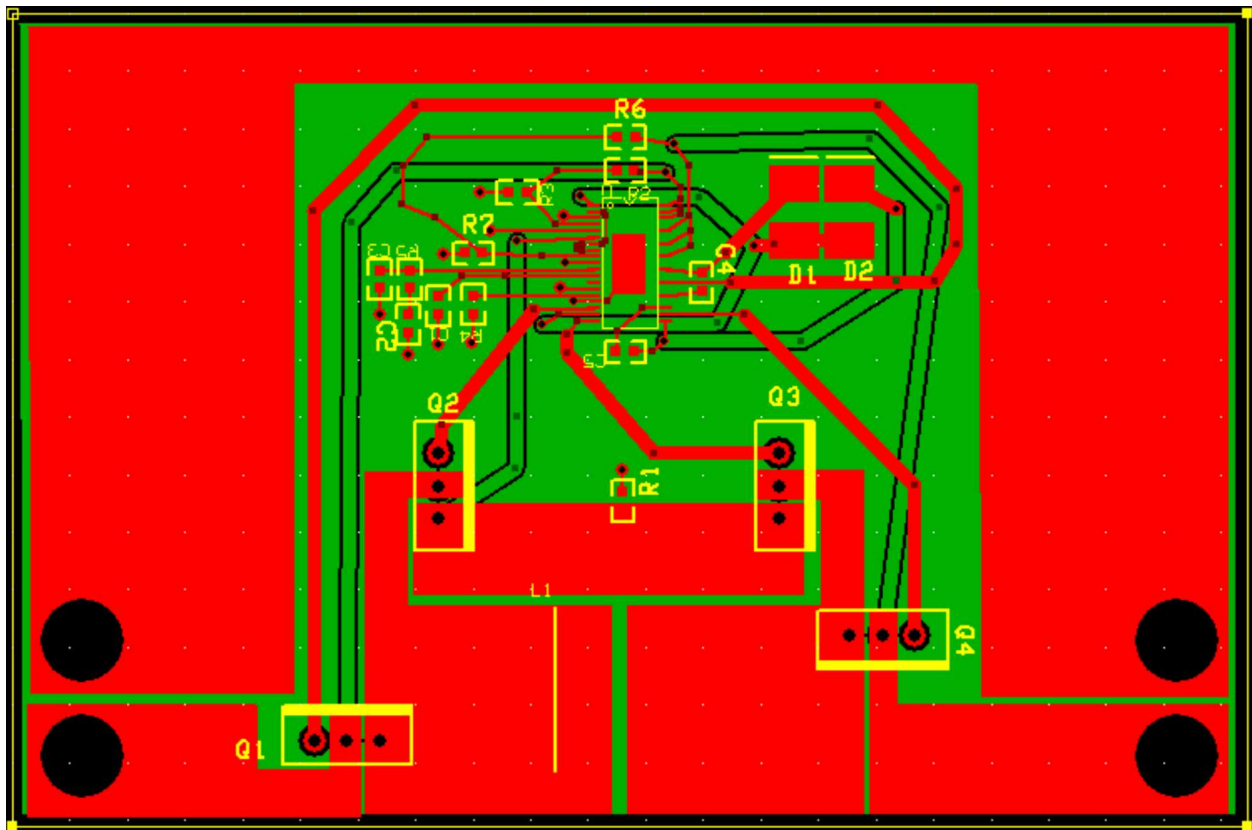


Figure 10: First Revision Two Layer PCB

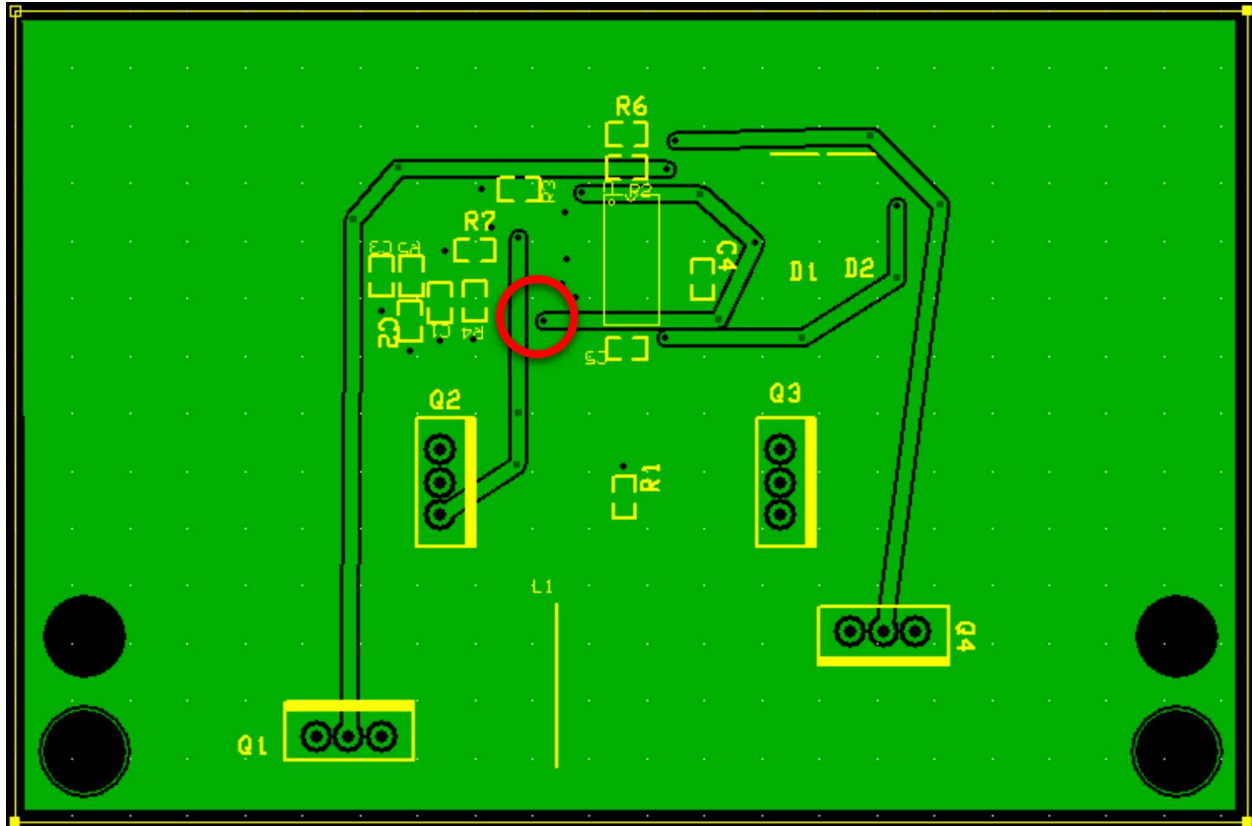


Figure 11: First Revision Bottom Layer

Revision 2

The second layout revision, shown in Figure 12, changes dramatically from the first revision, mainly due to the switch from a two layer to a four layer board. This allows for routing of all traces outside of the ground layers and the multi-layer option supports higher current capability, lower conduction drop, better thermal spreading, and substantially improved EMI performance [16]. This change allows for dramatically shorter gate traces and more efficient placement of the MOSFETs and diodes. The second revision also includes input and output capacitor place holders, sized in a future revision, and separation of the power and signal ground. This includes flipping locations of the input and output positive and negative terminals to shorten the ground return path.

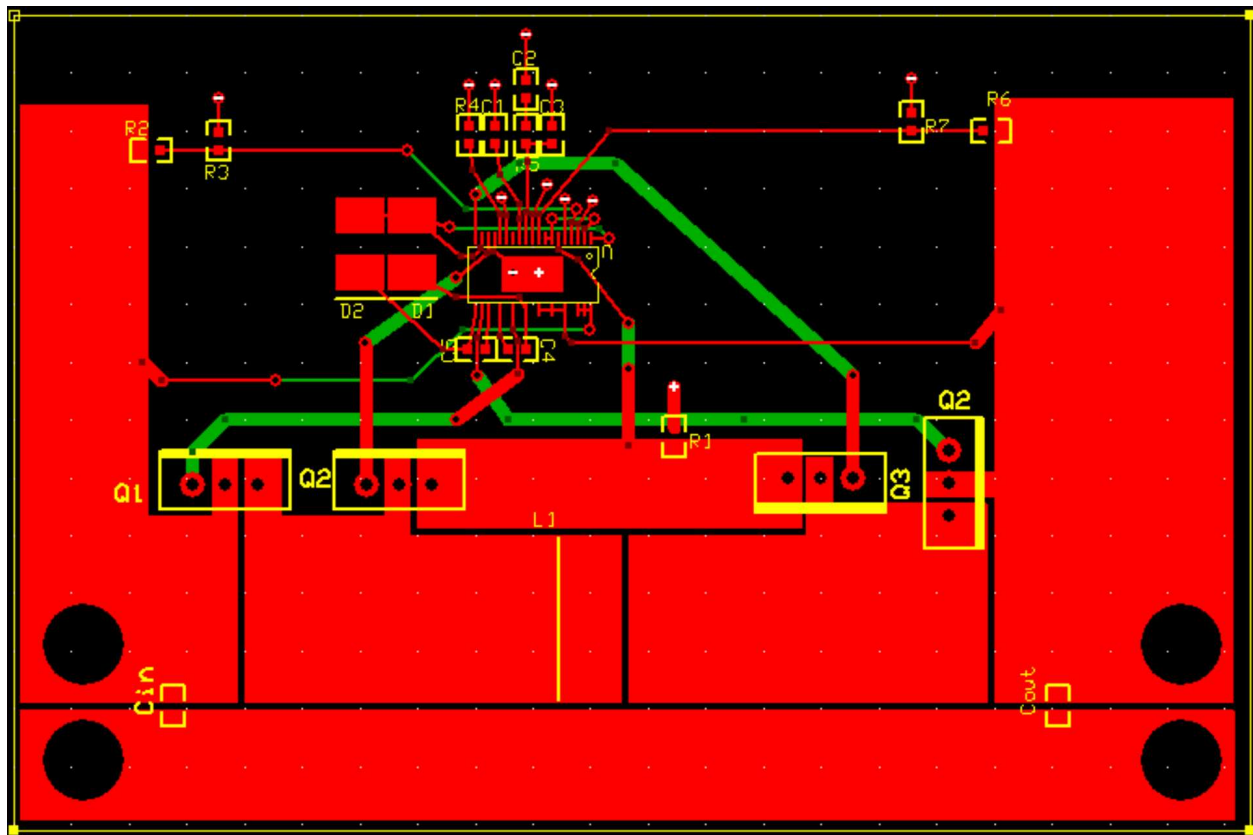


Figure 12: Second Revision Four Layer PCB Top and Bottom Layers

Drawbacks of the design come from the internal ground layers shown in Figures 13 and 14, and component sizing. The bottom section of the board consists of power ground and a trapezoidal signal ground region at the top of the board. In this layout design, the signal ground cuts off some of the ground return paths due to its trapezoidal shape.

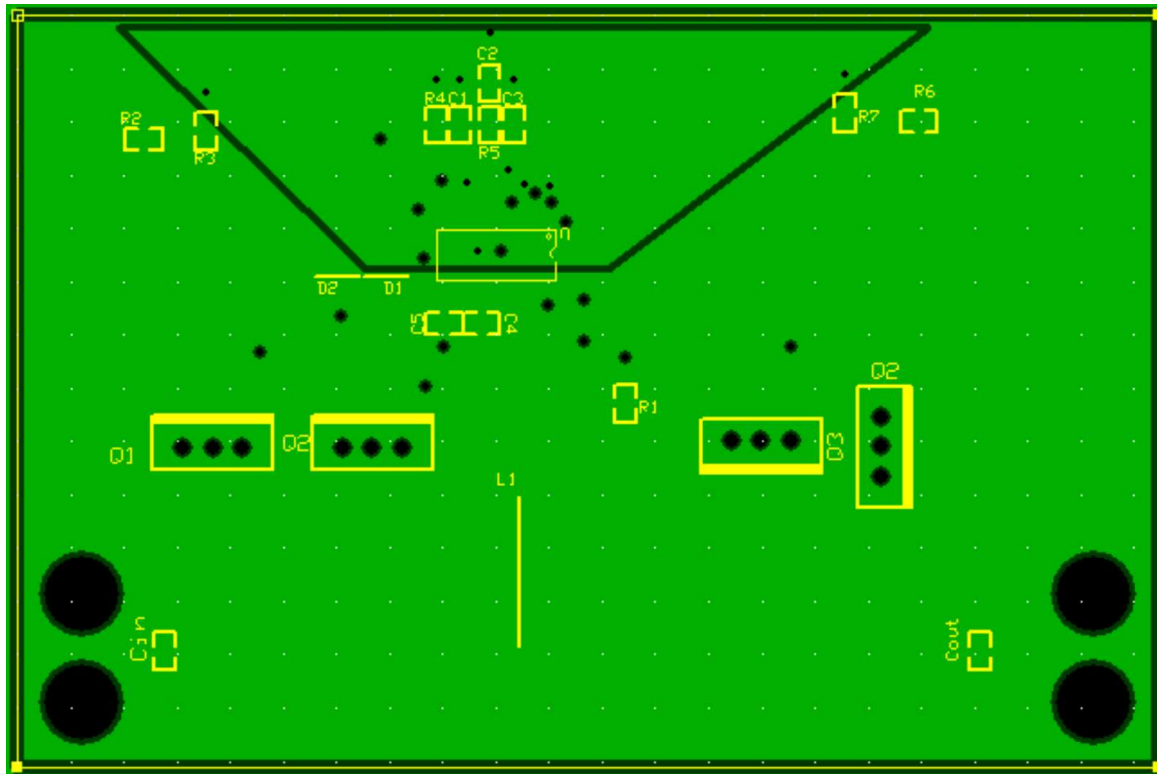


Figure 13: Second Revision Inner Ground Layer 1

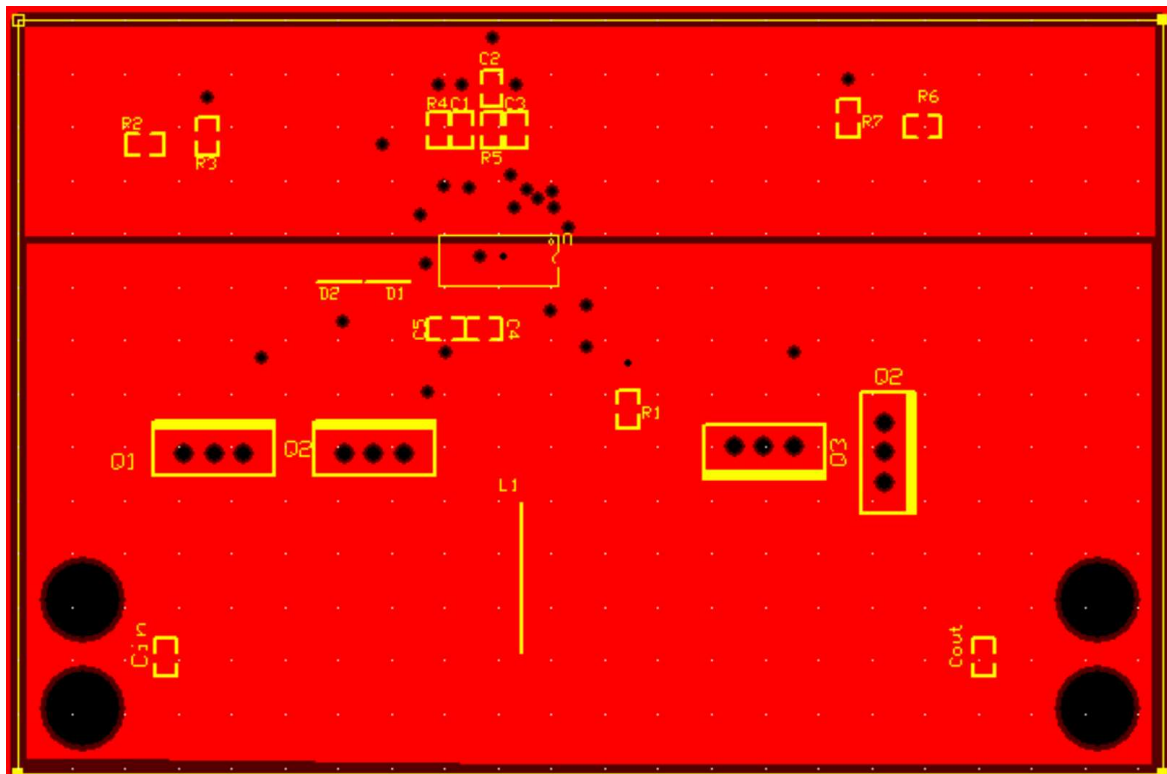


Figure 14: Second Revision Inner Ground Layer 2

Revision 3

The third revision, Figure 15, includes reshaping of the ground planes, addition of a bypass capacitor for the input and output resistor networks, correct sizing of the sense resistor, flooding the bottom layer with copper, adding vias to connect the different ground plane layers and removing ground from under the switching nodes on all layers. Revision three makes the board as close to ready for fabrication as possible, without having footprints for the heat sinks and input/output capacitors. In double checking the layout, an error was corrected in the connection of the switching nodes.

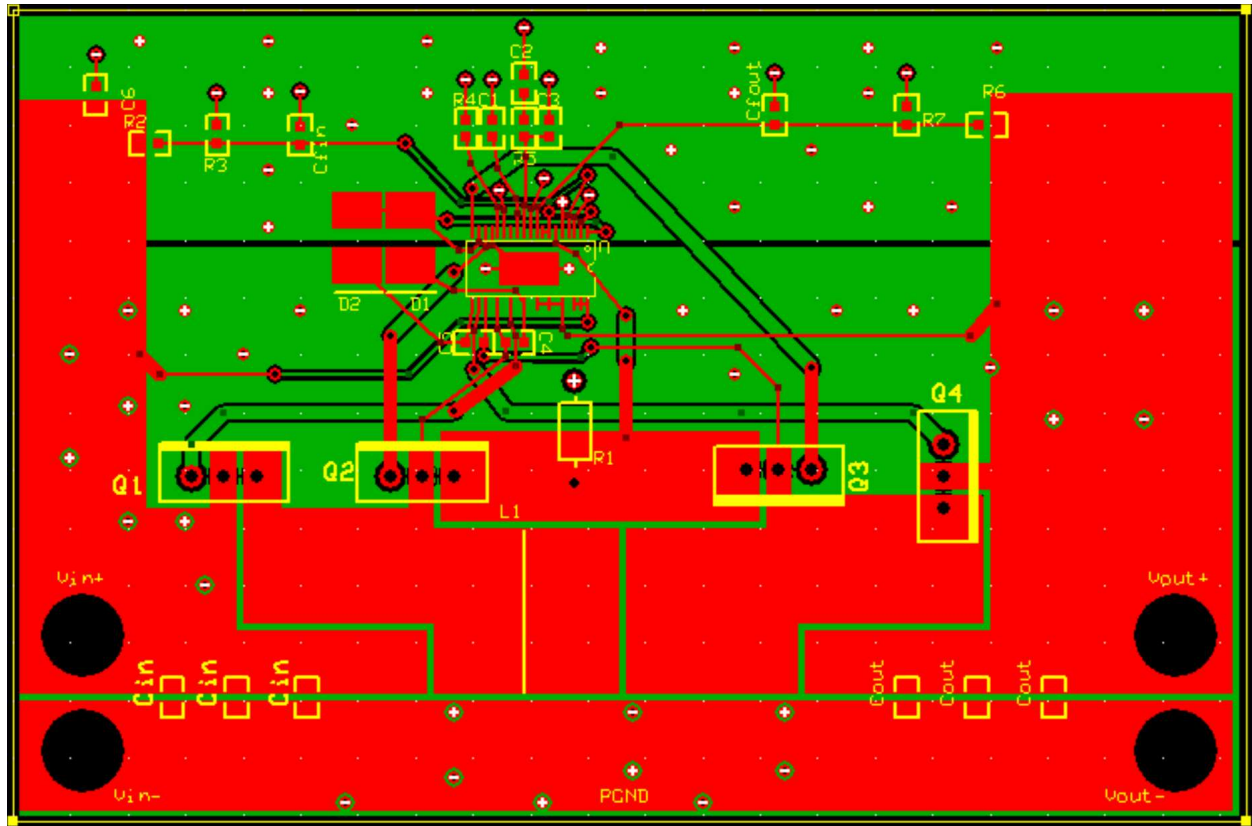


Figure 15: Third Revision Top and Bottom Layers

The top inner ground layer, shown in Figure 16, no longer has a trapezoidal shape for the signal ground. The top portion now represents signal ground and the bottom represents power ground.

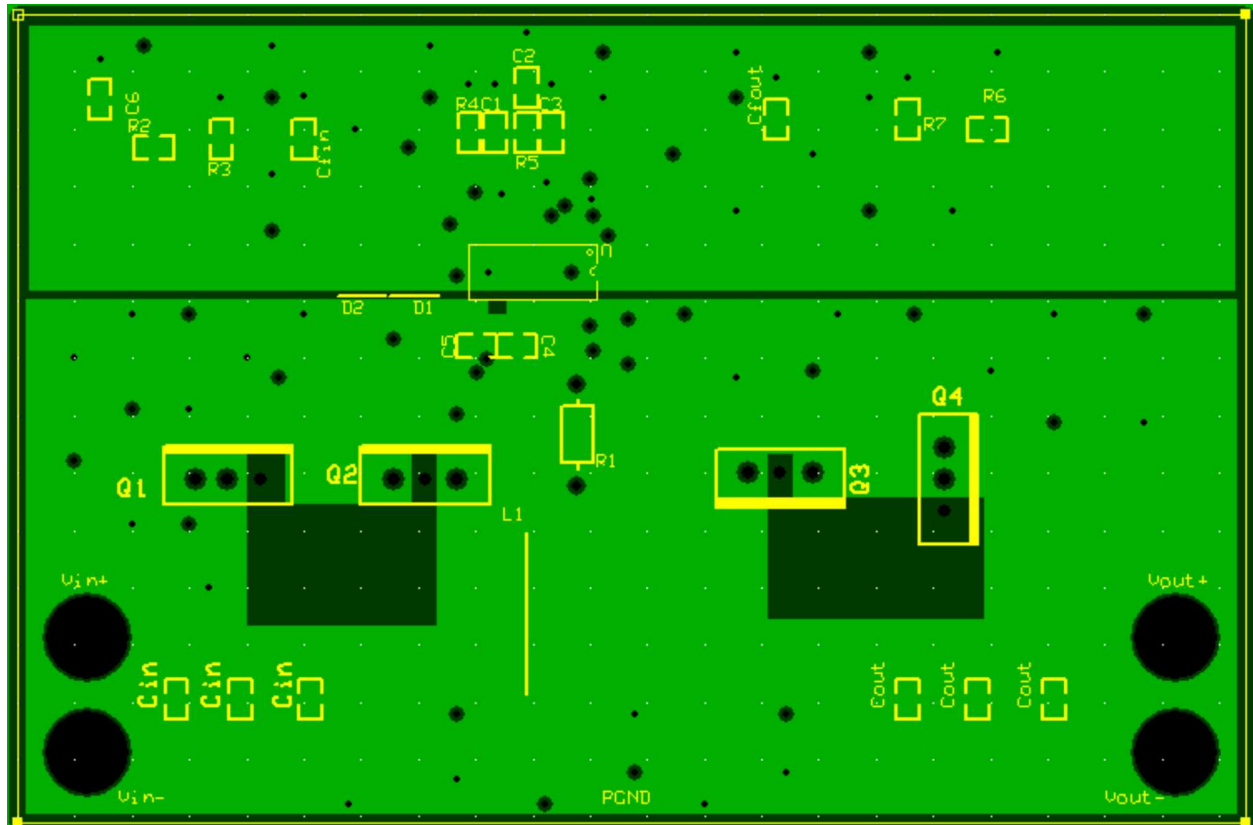


Figure 16: Third Revision Inner Ground Layer 1

Adjustments to the power ground, shown in Figure 17 by the blue circle, makes sure it covers all components in need of power ground.

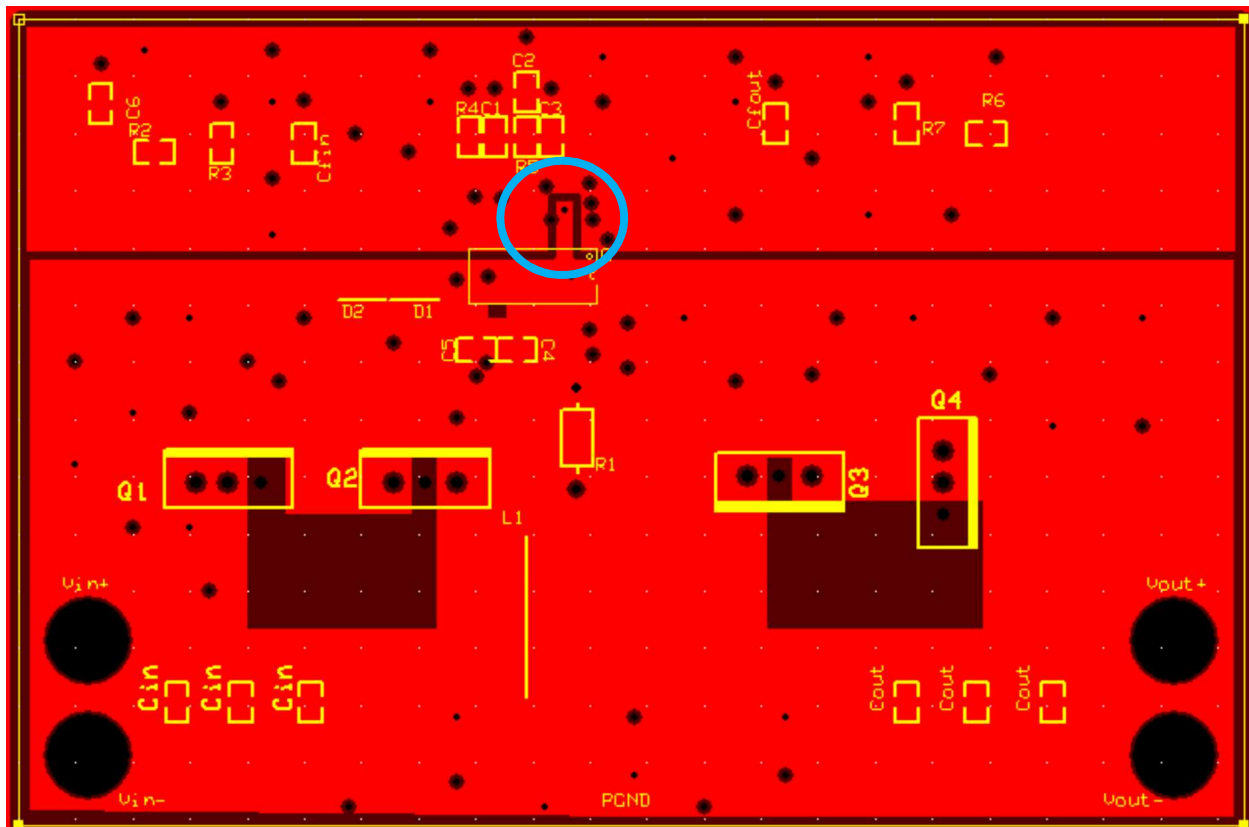


Figure 17: Third Revision Inner Ground Layer 2

Revision 4

The fourth revision, Figure 18, includes footprints for the MOSFET's heat sinks and the input and output capacitors, bigger vias on the gate traces for testing nodes and reshaping of the top power ground layer. In order to fit all the components on the board, the length of the board increased by 14mm. With the slightly bigger board, the power ground now wraps around the outside of board, allowing for better placement of the input and output capacitors. The movement of the MOSFET switches, due to the heatsink footprints, causes small changes in the placement of the switching nodes connecting the inductor and switches and the plane connecting the sense resistor to the switches.

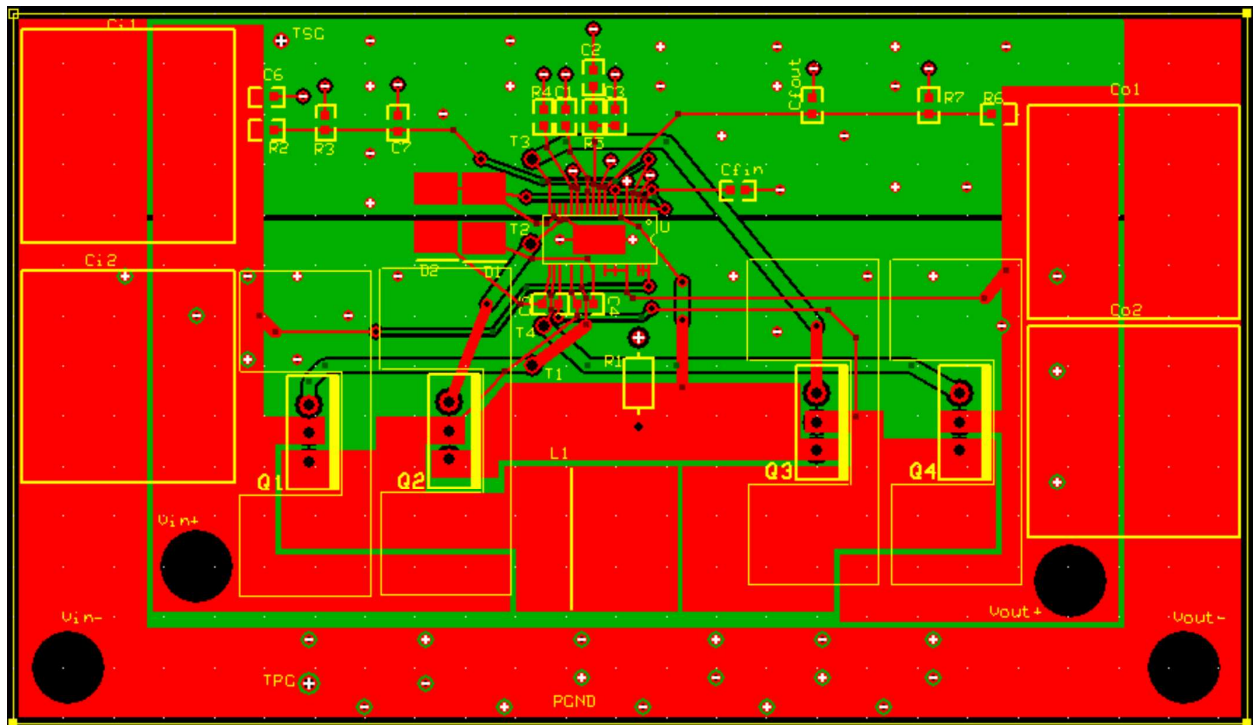


Figure 18: Fourth Revision Top and Bottom Layers

Final Revision

This revision includes a new heatsink footprint for the MOSFET's, mounting holes and a switch to KiCad design software. Switching to KiCad allows for more functionality and a smaller fabrication cost when compared to ExpressPCB. A few examples include, the ability to add traces to inner copper layers, footprint models that match available products and simplified trace routing. Due to the increased size of the new heatsinks, seen in Figure 19, the board size needs to increase. ExpressPCB increases the price of the board from \$81 to \$195 for boards that exceed 3.8"x2.5". Switching to KiCad allows for the fabrication process to be done at a different fabrication house, such as OSH Park. OSH Park charges \$10 per square inch for the board. With the board at 4.57"x3.25" the estimated cost of comes to \$148.53, saving almost \$50. The bigger heatsinks also force changes to the layout of the components on the board.

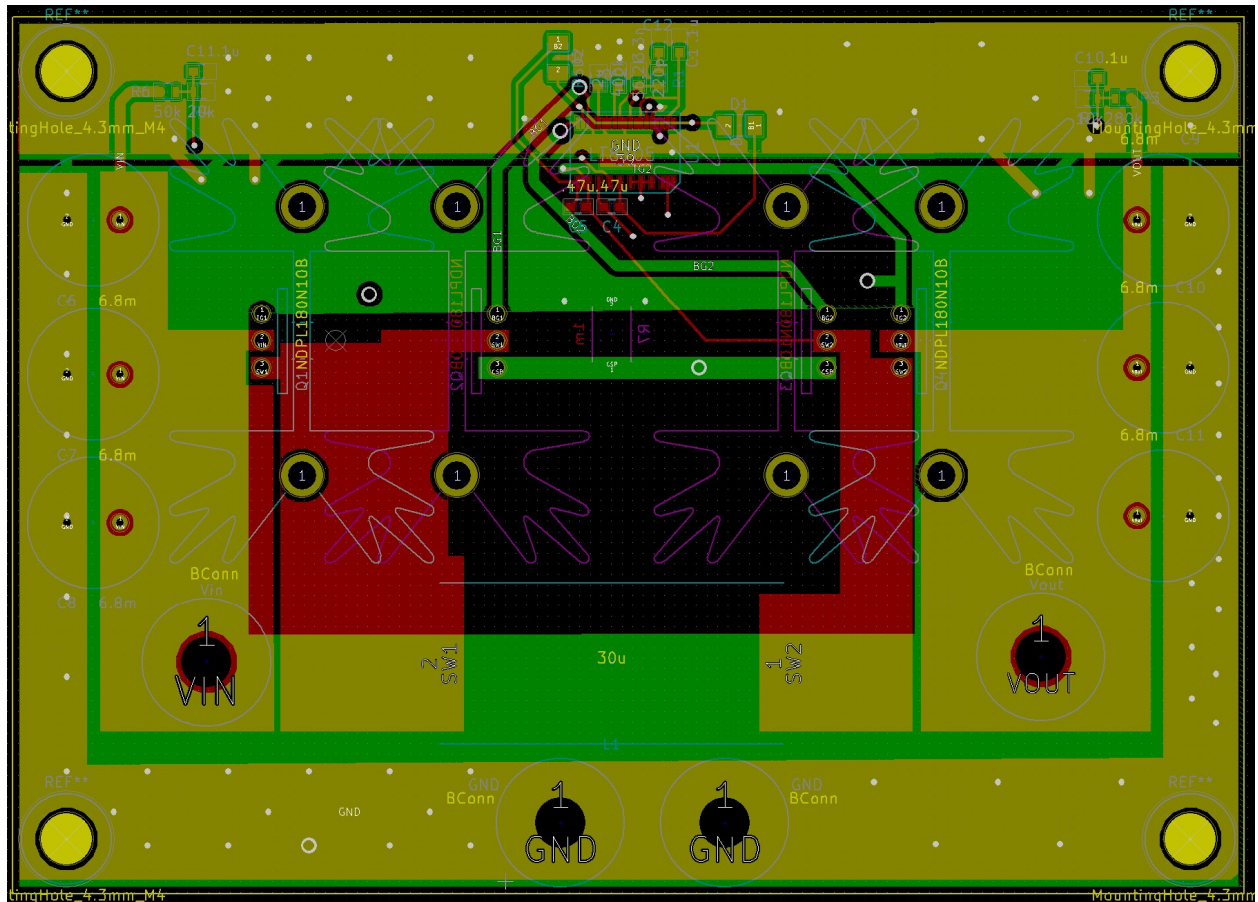


Figure 19: Final Revision Top and Bottom Layers

Other Heatsink Layout Consideration

As seen in Figure 19, the final design has two heatsinks on the top layer and two heat sinks on the bottom layer. Figure 20 shows another consideration for placement of the heatsinks.

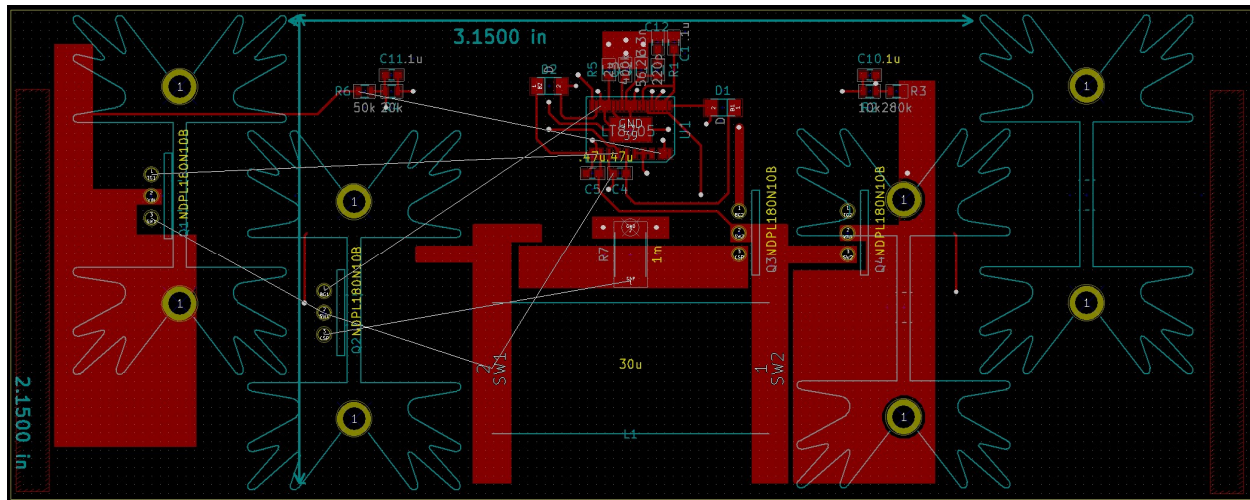


Figure 20: PCB with All Heatsinks on the Top Layer

Compared to the chosen option, this layout allows for all heatsinks to sit on the top layer. This decreases the depth of the board plus heatsinks by 2.5 inches. However, it increases the length of the board by 2.56 inches. That represents a large increase in fabrication cost which lead to the decision to use both the top and bottom layers for the heatsinks.

The following chapter sets up the testing procedures used to test the PCB shown in Figure 19. It also shows the results of the tests performed and compares them to theory.

Chapter 6: Testing

Setup

The test setup, shown in Figure 21, consists of the following equipment:

- DC Power Supply
- DC-DC Converter
- Electronic Load
- Oscilloscope
- 4 Banana to Banana wires
- 2 Oscilloscope Probes

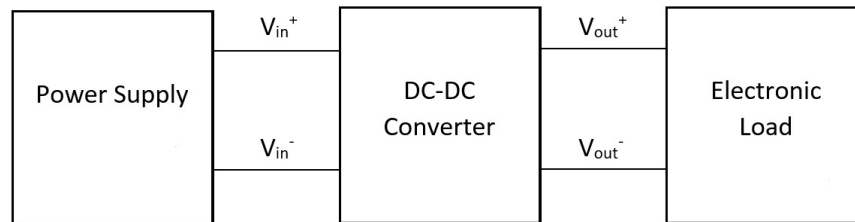


Figure 21: Test Setup

The electronic load used for testing, shown in Figure 22, functions in three different modes: constant current, constant voltage or constant resistance. Using constant current mode, the load functions by drawing a set amount of current from the converter and displaying the voltage or power across itself.



Figure 22: BK Precision's Electronic Load [6]

The electronic load has a power limit of 150W, voltage limit of 60V and current limit of 30A [6].

To start testing, set the electronic load to 36V, the desired input to the micro-inverter [18]. Next, set the DC power supply to a voltage in the midrange of voltages around 36V so that the converter does not stress when testing basic functionality. After connecting both the load and the power supply properly shield the PCB and turn them both on.

Predicted Results

Theoretically, the converter should operate in boost mode, shown in Figure 23, when applying a 24V input. This implies the following switch conditions, MOSFET Q1 on, Q2 off, Q3 switching and Q4 switching and an output of 36V. In Figure 23, Switch S_A represents switch Q1 on the PCB, S_B represents switch Q2, S_C represents switch Q3 and S_D represents switch Q4.

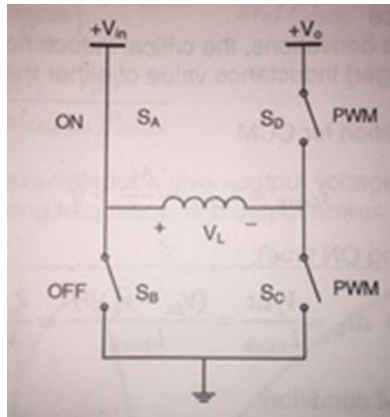


Figure 23: Switch Conditions for Boost Operation [19]

Correct operation of the circuit hinges on correct gate signals entering the MOSFETs. The MOSFET's have a minimum threshold voltage of 2V [22] and are designed to be switching at 155 kHz. Therefore, the gate waveforms should take the form of a square wave with a peak to peak voltage of 6V, a DC offset of 3V and a frequency of 155 kHz.

Measured Results

Testing the converter with this procedure results in no current flowing through the converter. Both the DC power supply and the electronic load show 0A. Testing found all switches on except for switch Q2. Figure 24 shows the gate signal entering Q2 with the input voltage set to 24V. The signal switches with a frequency of 179.63 kHz, has a peak to peak value of 130mV and an average value of 680 mV.

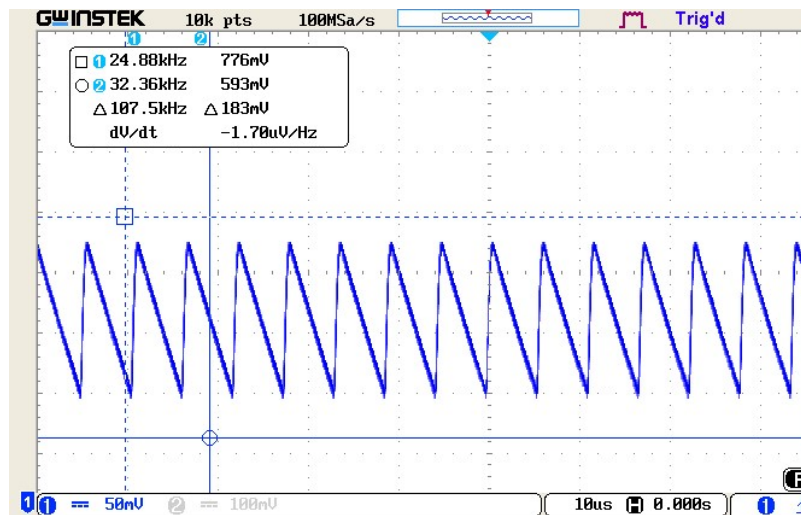


Figure 24: Gate Signal on Q2

This waveform indicates that the circuit does not operate correctly as it does not reach the MOSFET threshold voltage and should not switch under the given conditions. All other gate signals stayed at 0V during testing. Testing under buck conditions, $V_{in} > V_{out}$, provides the same results.

The following chapter discusses problems with the design process, quick board fixes that need to be improved and suggestions for future projects.

Chapter 7: Conclusion

Results of testing show that the converter does not operate as designed. Debugging and improving the current design of the DC-DC converter continues with ongoing and future projects within the EHFEM group.

This project did not meet its timing goals due to the extended design phase of the PCB. This did not allow enough time for design changes upon receiving the board or debugging the circuit once testing started.

As seen in the red box in Figure 25, a mix up in package size when creating the inductor footprint forced the use of two inductors connected in series. The footprint ended up twice the size as the inductors themselves. In order to build the circuit, two inductors were placed side by side, and electrically connected with solder between right pad of the left inductor and the left pad of the right inductor. This fix doubles the inductance, making it $44\ \mu\text{H}$ instead of $22\ \mu\text{H}$, which should improve the output voltage ripple but increase the startup time.

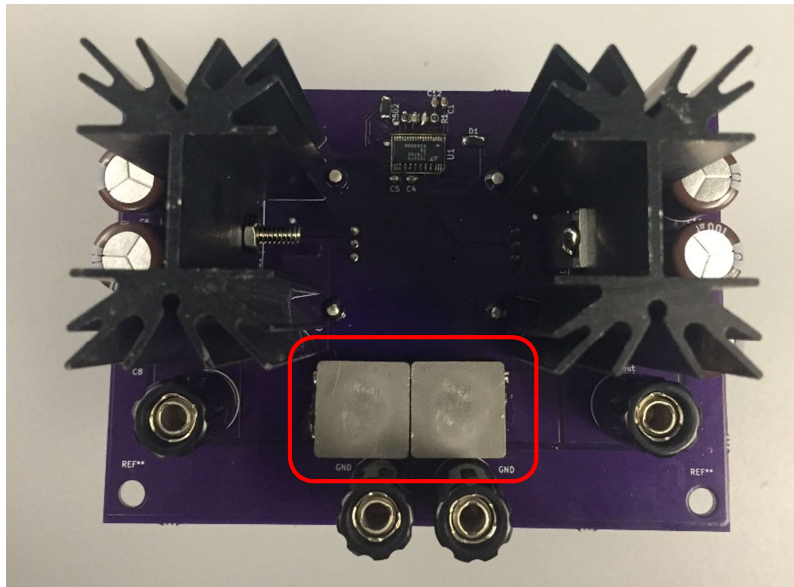


Figure 25: Top View of Converter

Connecting the sense resistor also required a quick fix due to the solder mask covering the sense resistor pads on the bottom layer of the PCB. Shown in Figure 26, scratching off the solder mask revealed the copper underneath, allowing placement of the sense resistor.

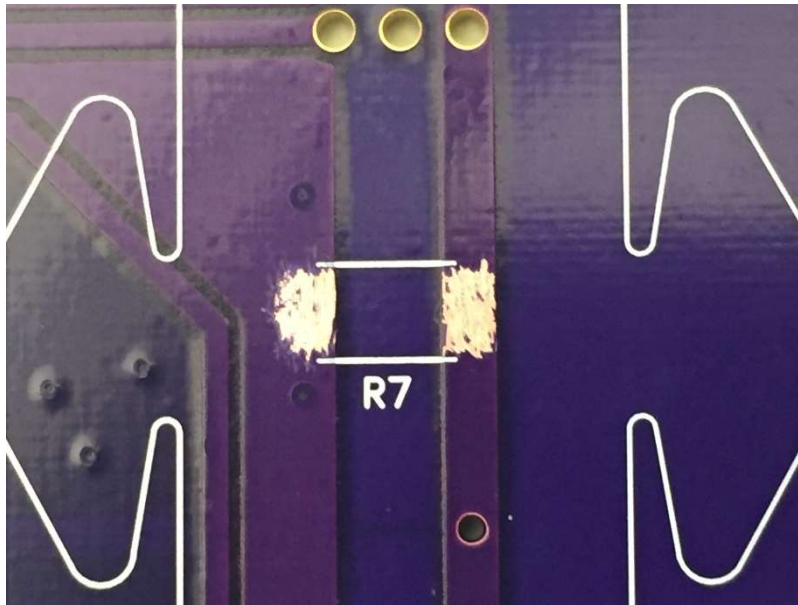


Figure 26: Hand Scratched Pads

While starting the PCB design process from scratch proved to be a learning experience, in order to complete a working design, future projects should start from the current design and fix it before trying to improve it. The entire PCB design process took three times longer than expected, future groups should plan for this during their project planning phase.

Suggested future improvements and projects:

- Research and consider designing an isolated topology DC-DC converter. After a recent talk with Dr. Taufik it seems that this may improve the efficiency for high power applications.
- Contact Life Fitness to work on a redesign of their exercise equipment that would include an accessible point for the EHFEM system to connect.

References

- [1] R. Ford and C. Coulston, *Design for Electrical and Computer Engineers*, McGraw-Hill, 2007, p. 37
- [2] *IEEE Std 1233, 1998 Edition*, p. 4 (10/36), DOI: 10.1109/IEEESTD.1998.88826
- [3] Linear Technology, “80V VIN and VOUT Synchronous 4-Switch Buck-Boost DC-DC Controller”, 2013. [Online]. Available: <http://cds.linear.com/docs/en/datasheet/8705fb.pdf>
- [4] B. Burk, R. Bhula, N. McKay, Energy Harvesting from Exercise Machines: LT8705 DC-DC Conversion for Elliptical Trainer, California Polytechnic State University, Elect. Eng., Senior Project, 2014. [Online]. Available: <http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1295&context=eesp>
- [5] Taufik, Introduction to Power Electronics, San Luis Obispo, CA: California Polytechnic State University, 2009.
- [6] BK Precision, “Model 8540 60V/30A/150W DC Electronic Load”, 2008. [Online]. Available: <http://www.mcmelectronics.com/content/ProductData/Manuals/73-1225.pdf>
- [7] Wong, M. Energy Harvesting From Exercise Machines - DC-DC Buck Boost Converter (LT3791), California Polytechnic State University, Elect. Eng., Senior Project, 2014. [Online]. Available: <http://digitalcommons.calpoly.edu/eesp/265/>
- [8] Funsten, E. and Kiddoo, C. Protection System, California Polytechnic State University, Senior Project, June 2014. [Online]. Available: <http://digitalcommons.calpoly.edu/eesp/259/>
- [9] D. Braun, “Braun’s Senior Projects,” California Polytechnic State University, January 2014.
- [10] R. Turner and Z. Weiler, DC-DC Converter Input Protection System: From the Energy Harvesting from Exercise Machines project, Electrical Engineering, Senior Project, 2013. Available: <http://digitalcommons.calpoly.edu/eesp/214/>
- [11] J. Hilario, Energy Harvesting from Exercise Machines using Four-Switch Buck-Boost Technology, California Polytechnic State University, Elect. Eng., M.S. Thesis, 2011. [Online]. Available: <http://digitalcommons.calpoly.edu/cgi/viewcontent.cgi?article=1541&context=theses>
- [12] S. Chu and B. Yoo, BUCK-BOOST DC-DC CONVERTER with INPUT PROTECTION SYSTEM FOR THE ENERGY HARVESTING from EXERCISE MACHINES PROJECT, California Polytechnic State University, Electrical Engineering Senior Project, 2014. [Online]. Available: <http://digitalcommons.calpoly.edu/eesp/258/>

- [13] Ieee.org, 'IEEE Code of Ethics', 2015. [Online]. Available: <http://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: 04- Nov- 2015].
- [14] S. Adams, 'Forbes Welcome', *Forbes.com*, 2015. [Online]. Available: <http://www.forbes.com/sites/susanadams/2013/01/24/college-degrees-with-the-highest-starting-salaries-2/>. [Accessed: 12- Nov- 2015].
- [15] Statista, 'Number of gyms in the US (health/fitness center) 2000-2014 | Statistic', 2015. [Online]. Available: <http://www.statista.com/statistics/244922/us-fitness-centers-und-health-clubs/>. [Accessed: 07- Dec- 2015].
- [16] T. Hegarty, "DC/DC converter PCB layout, Part 1", EDN, 2015. [Online]. Available: <http://www.edn.com/design/power-management/4439695/2/DC-DC-converter-PCB-layout--Part-1>. [Accessed: 13- Feb- 2016].
- [17] "ExpressPCB", ExpressPCB, 2016. [Online]. Available: <http://www.expresspcb.com/>. [Accessed: 05- Jan- 2016].
- [18] Enphase Energy, Inc., Enphase Microinverter M215 Datasheet, 2013. [Online]. Available: http://enphase.org/downloads/Enphase_M215_Datasheet.pdf.
- [19] Taufik, Power Supply Design: Components and Control, San Luis Obispo, CA: California Polytechnic State University, 2016.
- [20] Automation Direct, What Do The NEMA Ratings Mean? 2016. [Online]. Available: <https://www.automationdirect.com/static/specs/encnemaratings.pdf>
- [21] D. Braun, "EE 460 – Senior Project Preparation," California Polytechnic State University, September 2015.
- [22] ON Semiconductor, NDPL180N10B Power MOSFET, 2016. [Online]. Available: <http://www.mouser.com/ds/2/308/NDPL180N10B-D-587751.pdf>

Appendices

A. Analysis of Senior Project Design

Energy Harvesting from Exercise Machines: Buck Boost DC to DC Converter with LT8705 Controller

1. Summary of Functional Requirements

As described in the Functional Decomposition portion of this report, the Energy Harvesting from Exercise Machines project consists of a system that takes in energy generated by a user on a piece of exercise equipment and converts it to power and sends it to the grid. The system takes in an input voltage in the range of 5V – 65V, from the user, at a maximum current of 5A. This energy gets converted into a 36V output with an average of 5A.

2. Primary Constraints

Refer to Chapter 2: Customer Needs, Requirements and Specifications

3. Economic Impacts

The economic impacts of the EHFEM system:

- Cost of labor for design engineer
- Cost of labor for manufacturers
- Cost of materials (See Figure 4 for a complete breakdown)
- Natural resources
- Cost of repair technicians

The one responsible for the cost of the project depends on the overall success of the project. At the beginning, the designer and manufacturer assume all responsibility for the cost. They pay the material cost, listed in Table 5, and the labor cost, also listed in chapter 4. Once sold, the purchasing recreation center assumes responsibility for the cost. They buy each unit from the designer/manufacturer, whom has set the price in order to make a profit. According to [4], after approximately two and a quarter years, the EHFEM system pays for itself with the accumulated utility bill savings. From that point on the utility company assumes the cost of the product. Throughout the 10-15 year life cycle of the system the recreation center or the manufacturer would assume responsibility for the cost of any maintenance required.

Extra testing costs include, purchasing an exercise machine (done already for the EHFEM project) and prototyping boards for development. Each design, build, test cycle outlined in the project planning section brings up new errors that need fixing. This results in anything from new parts, more parts, new designs, etc. With these included, the project does not become profitable unless it becomes a mainstream item in recreation centers.

The natural resources cost likely affects future generations, not our own. Products like this deplete the Earth's store of fossil fuels due to their manufacturing and transportation needs. They also deplete Earth's store of semi-conductors, such as silicon, and metals used in the products integrated circuits and other components. With the depletion of these items, the next

generations may not possess enough natural resources to develop new technology in the way we do today. This results in the need to find new ways to survive with completely new technology.

The cost of repair technicians has both positive and negative aspects. From the view of the party paying for them, it creates a negative implication because of the extra cost from the product. However, on the positive side, it creates employment wherever the product ends up because of the need for specially trained people to fix any problems that arise with the product.

4. **Commercial Manufacturing**

Based on the number of recreation centers in the United States, if manufactured on a commercial basis, selling one unit to each recreation center, the product would sell an estimated 34,460 units [15]. The material and labor cost creates a manufacturing cost of roughly \$150. Making a profit requires placing the system at 15% above the manufacturing price, \$172.50. This equates to a profit of \$675,000 realistically, closer to \$500,000 after startup costs. This includes the estimation that each recreation center buying only one EHFEM system, the more likely situation entails them buying enough to outfit all of whichever type of exercise equipment they use it for. This would result in them cutting their utility cost by even more and therefore decreasing the amount of time needed to pay back each unit.

There always arises the uncertainty of how many units might sell, which leaves the non-recoverable cost of units not sold. This uncertainty comes from the competition of other manufacturers and the interest level of different recreation centers. Taking this into account, if the manufacturer makes 30,000 units of the product, with the cost and price listed above, they must sell at least 26,087 units in order to break even. If each recreation center bought on average 5 units, they would have to sell to at least 5,217 recreation centers. That amount represents 15.14% of the market share for this product.

5. **Environmental Impact**

The EHFEM has a positive overall impact on the environment. As described in the economic impact section of this analysis, the design and manufacturing process depletes natural resources in order to build the product. This harmful impact on future generation's ability to innovate leads to problems. Once one natural resource runs out, another needs to surface. The cycle repeats until nothing usable remains, unless the root of the problem is address. A more renewable manufacturing process needs to be developed. Without that, future generations may not have the power to make anything. Once implemented, the system limits the natural resources needed to power recreation centers across the world, generating a small positive step in the right direction.

6. **Manufacturability**

The main issue with manufacturability comes from the process of manufacturing the multilayer board used in the final system. Necessary decisions include weighing the effects of outsourcing this process against alternatives such as completing the process in house or redesigning the system.

Other issues that arise pertain to assembly and installation. Economic feasibility requires the consideration of mass production techniques. Once manufactured, the process of installing the product in recreation centers also presents an issue. Each recreation center may use a different style of exercise machine, creating the problem of where to attach the product. Then comes the decision of who installs the system, the manufacturer or the recreation center themselves.

7. Sustainability

Efficient design of the system creates minimal sustainability impacts. The environment impact section contains some harmful impacts, exploration of more follows in this section. Incorrect design of the heat flow through the components provides the biggest challenge. Improperly consideration of heat flow in the design, leads to the product needing extra maintenance down the road or even needing a complete redesign. This would increase the amount of non-degradable material in the landfill, creating a negative impact on the environment. As described in the environmental portion of this analysis, the overall impact should increase the sustainability by limiting the amount of natural resources used by humans. In order to improve the design, implementation of a different controller could improve the converters efficiency. However, with current technology, not much can improve upon current designs. The biggest improvements need to come with technological advancements in the field of converters.

Outside the scope of this project, there arises the issue described in the environment impact section about future generations needing a way to power manufacturing plants. With the depletion of fossil fuels, manufacturing plants may need exclusively renewable power. While many work on a big solution to this problem, the answer may need to come in the form of smaller amounts of renewable energy, such as the amounts created by the EHFEM project and other smaller sources like piezo electrics. On a per unit scale, these systems may not create much, however, many small sources combined together create a large impact.

8. Ethical Implications

The system design presents the main ethical dilemmas. Section 1 of the IEEE Code of Ethics, [13], states, "...to accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment." And as outlined by Section 6 of the IEEE Code of Ethics, one must only partake in technological tasks for others if qualified by training or experience. Improper system design creates potential hazard to the users of the exercise machines. As mentioned, the heat generated in the system allows for the potential to burn the exercise machine users. The user input from the exercise machine represents a wide range of voltages and currents that could result in heat spikes, requiring solid design techniques to avoid stated safety issues.

Section 3 of the IEEE Code of Ethics also plays a role in this product. It states, "...to be honest and realistic in stating claims or estimates based on available data." When attempting to sell the product to recreation centers, sellers want to make it seem as if the product pays for itself in the shortest amount of time possible. Any data given out on this claim must have accuracy and achievability by the system.

An ethical egoism argument also applies for this system. In order to achieve a system that creates a more sustainable environment, design of the system keeps the environment in mind throughout the entire project. This does not always lead to the most profitable design approach for the system. Certain components that do not comply with standards such as RoHS, may cost less and still get the job done. Using these environmentally unfriendly components would lead to a greater profit for the designer but a larger negative impact on the environment. Ethical egoism roots in the premise that people should act in their own self-interest. While the designer may have it in his self-interest to design an environmentally friendly system, shortcuts in the design present themselves, allowing designers to create more profit for themselves. In order to comply with all safety and legal standards, designers must use caution in their design shortcuts.

9. Health and Safety

The final four entries of Table 1 outline the safety concerns. The system must abide by all standards set for exercise equipment as well as any manufactured electrical system.

10. Social and Political Implications

This project hits on a key environmentally political issue, the depletion of Earth's natural resources. Debates on where the solution could come from include devices like the EHFEM system. Others address the issue at the utility side, and more radical ideas address the problem at humanity's roots. This major political issue may not go anywhere anytime soon. In the meantime, projects like this make a small impact in the right direction.

The direct stakeholders of this project, the manufacturers and the customers, sustain impacts of profit, cost and savings. Time, the biggest cost for both stakeholders, comes from the design time and time spent waiting for the product to pay for itself. This effects the labor costs and the savings period of the product. Various other indirect stakeholders are involved, including the participants of the recreation centers. Their costs include, expend their energy in order to benefit the savings of the recreation center and the sustainability of their environment. Some may make the argument that moral issues come into play when stealing a participant's energy in order to benefit the recreation center. However, participants receive benefits such as the sustainability of their environment, and increased health. This argument has strong points on both sides and arguments may continue for some time to come.

Other smaller stakeholders include the clubs that could receive increased funding due to the extra money in ASI's budget, companies that sell materials used in the manufacturing of the system, designers of exercise equipment and many more.

11. Development

In order to complete this project I need to learn more about the workings of DC-DC converts as well as gain more experience in the design-built-test cycle.

See literary search above in the references section.